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Multi-Disciplinary Constraints in Aerodynamic Design

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Abstract

Paper nr. 11

A long tradition of aerodynamic design of combat vehicles shows that the expression of the targets and the constraints in the design are always difficult to select. Present long iteration processes hide such variable target/constraints continuous reassessment. Every processes of design unable to have flexibility in target/constraint handling is unusable.

Fortunately, the geometrical constraints are now better handled in new CAD software with features modeling.

The present development of new constrained features modeling will be described from its basic expression to the more complex and variable topology configuration.

Fitting the optimization process to the physics of multidisciplinary constraints may not be as easy as for geometry. It is proposed to select a family of constrained variations of geometry, each able to cope with a specific physical optimization and to generate a multiprojection of the multi-constrained operators. Some conceptual examples of such processes will be presented in the case of aeroelastic design, electromagnetic design and actively controlled configurations with variable geometry for improvement of flow control. The specific domains of use of deterministic and stochastic (genetic) algorithm and of self-adaptation by training (neural network) will be assessed.

New strategies will be proposed for sharing the work of optimization between different companies cooperating to the design of advanced aerospace vehicles.

Paper presented at the RTO AVT Symposium on "Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment", held in Ottawa, Canada, 18-21 October 1999, and published in RTO MP-35.

0. <u>INTRODUCTION</u>

0.1. Past and future in basic design

Definition and data detailed qualification of advanced flight vehicles are becoming very difficult task for design in aerospace industry. Many experts are saying that the problems and their optimal solving procedures are now order of magnitude more complex with the new multidisciplinary requirements.

However the consideration of what was done before does not support the historical theory of past design only devoted to separated optimisation in each discipline ; multidisciplinary requirements were always present in the mind of the designers but only in a global intuition due to the lack of appropriate tools, but not of appropriate exchange between specialists. In fact it becomes a problem with the increase in size of the design office at the preliminary stage of design and much more in the development phasis. The number of experimental and numerical data has dramatically increased. Much more precise evaluations in each discipline and their sensitivity to interface with other discipline are available but true multidisciplinary work, at the peak of complexity and cost are less available at the time where human exchange become harder due to the number of specialists involved in the final choices. The synthesis of their studies becomes problematic whereas, in the past, global estimation of complex phenomena, multidisciplinary or not, was present for tractable although rough optimisation.

So the problems are first human and secondly of availability of convenient engineering tools.

0.2 Human problem - Organization methodology

The number of stages in decision making is well known as major parameter in the efficiency of a company. It is particularly true in multidisciplinary design whatever the help of convenient tools. The driving team in the design is a "trinom" : a trinom is a group of three men who have to work together in a close manner to succeed the integration of the three major general disciplines of importance in design : the system analysist, the architect and the shape designer. These three men are working under the supervision of the chief engineer. Denomination may be variable in each company but the functional attribute cannot change. It covers the three main drivers in design plus the interface and convergence leader :

1/ Future product seen as a system fulfilling given tasks for an operator, eventually in a more general system of defence, transportation ... Major interest for the system leader is to afford global performance and to share the contribution of each part of the system to the efficiency of the product by convenient allocation of targets in performances for platform and sensors and weapons.

2/ Future product seen as a technical achievement with the best cost - efficiency of each physical item as contributor to the elementary performances needed for support of global performances and cost of the system.

3/ Future product seen as a real hardware and software product, easy to manufacture, test and operate because detailed design is adjusted to the production and operation.

It is now easy to build a tree of technical relations derived from the "trinom" as the group supporting the final decisions of the engineering leader. The problem will be to have small number of people reporting to the trinom and large number of specialists helping them to succeed the multidisciplinary balance at the higher level. The 1 and 2 facets of the multidisciplinary work need specific tools for evaluation of complex multidisciplinary interactions and first adequate interaction between specialist involved. The facet 3 is more a user of output of optimisation of technical parameters but it appears as the main dealer of constraints : geometrical, industrial and economical constraints.
With convenient hierarchy that may be achieved with minimum number of levels for avoiding loss of confidence and of oral traditions (much more effective that any note or listings or figures).

0.3 General technical tools for multidisciplinary work

At this level, we consider the 3 items ; we can express them in another perspective as builders of three products :

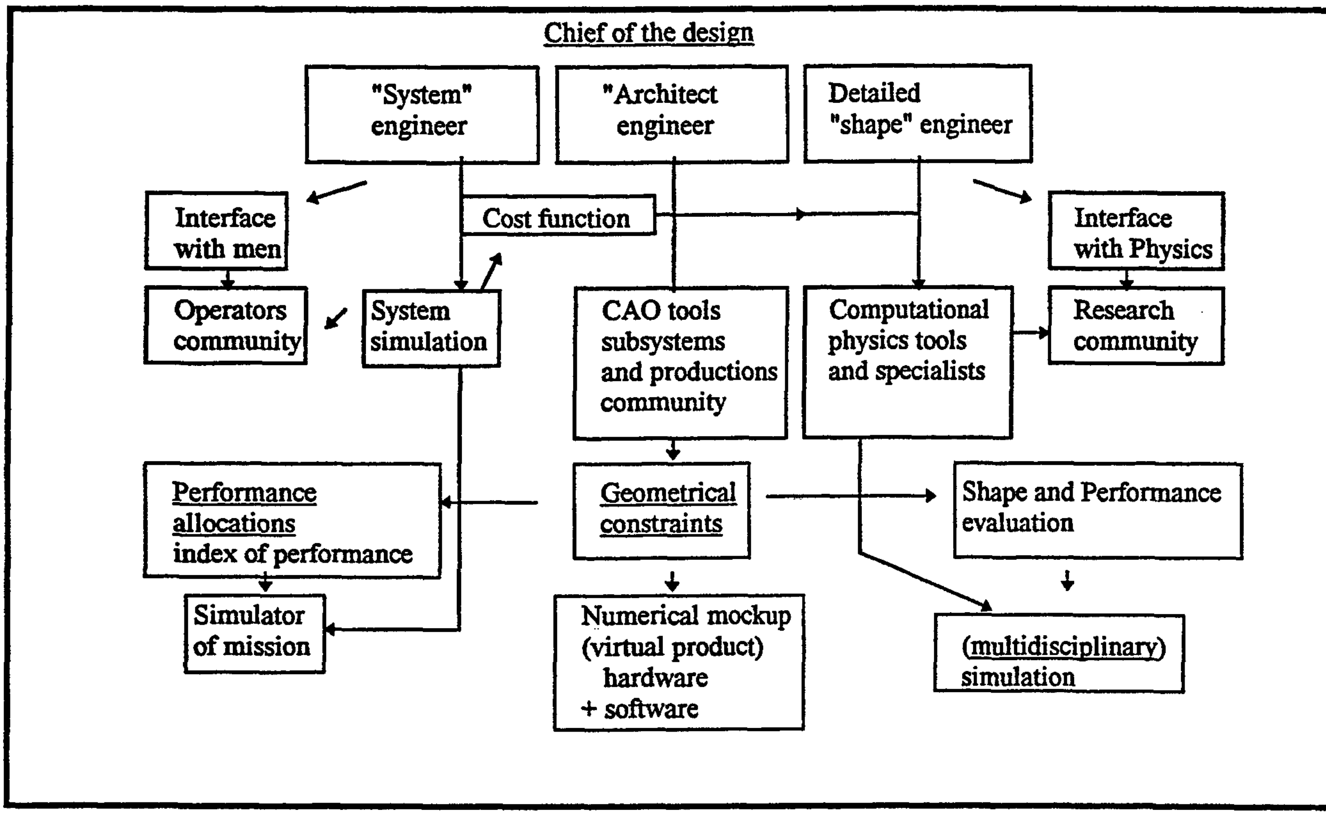
- The system engineer <u>master objective</u> with allocation of performance targets. It needs specific system tools at two levels for building as products :
- First global estimation - second detailed prediction of performance - variations with characteristic parameters of interface between different disciplines that share the allocation of performances : for example, the size of the radar antenna and the electromagnetic detectability and the speed of the flying machine. Major output is specifications for the cost and/or performance index to be declined for each specialist. Its major tool is a mission simulator.

The "architect" engineer <u>master a set of constraints</u> that minimize the size weight and cost of the final vehicle taking in account all the allocation of volume and location for structural parts or fuel or engines ... . If the margins for tolerance, reparation and operations are included, it is easily seen that

reduction in size, weight and cost appears as bounded by geometrical constraints that are the major output of a good architecture. Major output is a virtual model or numerical mockup

The "physicist" and "shape" engineer master the physics of the final vehicle because the laws of the physics bound the achievements of the systems in performance and the margins taken versus limits of the physics are a measurement of the "state of the art" in each discipline. Its major output is now a virtual model of computation (simulation) of detailed performances figures and physical parameters necessary to the evaluation of the performance index and determination of each real hardware and software.

Due to the fact that the major interface between the second and third partner of the trinom is geometrical, and that the major stresses are at the outer limit of structure, the skin of any aerospace product is critical in the design loop, it is convenient to speak of the output of the third engineer as "shape" engineer and to summary the relationship in the trinom and their tools in the following table :



Generally the multidisciplinary work is considered only on the side of the "physics and shape engineer" and the teams of specialist that he federates. But this table shows that it is a true cooperative work where the function to optimize is coming from system engineer and the constraints from the "architect engineer" as a prerequesite to multidisciplinary optimisation (M.D.O.).

0.4 Gradual concepts to incorporate in M.D.O.

The major problem in optimization with many variables is to evaluate with reduced number of "constrained" parameters cost function and its derivatives sensitivity analysis.

This paper is so organized as follows : first, geometrical constraints are taken as an example of reduction of number of parameters involved in multidisciplinary optimization. Next a thorough analysis of the rationale of physics related to variation in plysics emphasized the importance of numerical simulation and its validation in any multidisciplinary work. In conclusion some paths to cooperative multidisciplinary work between different companies will be proposed.

1.0. The problem of "constrained" geometry

First C.A.D. codes were derived from a mimic of the building of drawings in the design office with appropriate and traditional parameters and line and axis of reference. It excludes any direct volume generation and any variable parametrization of the quotations, so it excludes any distorsion, contraction or dilatation of separate parameters except the very scale of the part described. Such a definition is complete as is needed for a manufacturing plant, except some additive elements that appears by themself in the fabrication as for example the filets generated by path of a round cutting tool. Some elements defining completely the part may have to be added in the past to C.A.D. by manufacturing team, but now the effort tend to have complete geometry with details included in geometric data base. Thus it is possible to avoid hardware for mock-up and to rely on a completely virtual mock-up.

However the complexity of geometry is becoming so large that the preliminary design have to escape to so-detailed data base by simpler geometrical definition with the just-needed parametric description. It is the first effort to push in order to minimize the optimisation cost ; but it assumes the selection of relevant parameters, and the possibility of easy refinement or simplification of the geometric shapes, that can be done interactively if a trace-back of the work of definition on an interactive console is available. Parametric definition itself means that the tridimensional geometrical package of C.A.D. is able to reconstruct any complex shape for a given set of its basic parameters as retained in the definition. Such a parametric definition of the lines , surfaces and volumes is called : definition by "features" ; it has to give continuous threedimensional shapes varying with a continuous variations of the parameters. It is not generally possible outside of a limited range of variation of the parameters due to topological constraints : for example a torus has no interpenetration if the radius of centers is larger than radius of the basic circle and such interpenetration may be excluded if the volume of the torus is used as tank/link in geometry may also be excluded by stress or aerodynamic requirements.

So there appear two types of constraints :
- first topological
- second user or designer constraints as required by a specialist.

We may notice as example of architect or physics specialist requirements : the continuity in curvature for transonic design of airfoil and the generation by straight lines for easy fabrication of skins or fast milling.

1.1 The geometrical subset of constrainted shapes

We may include the previous requirement in the geometrical data base with features if the following rules are embedded in the variable geometrical package :

- for a given set of parameters only one shape is obtained

- for a given set of parameters continuity is enforced at the level of second order (aerodynamics) or first order (stress and electrodynamics) or zero order (part assembly)

- boundaries of change in topology with parameter variations may be easily computed : inequalities in the space of parameters may be then known, as a dual approach of acceptable topology (topology constraints).

- interaction between volumes or surfaces or lines may be precisely computed in order to take in account any architectural containment (e.g. volume of engine in a fuselage, undercarriage retraction without interference with a store ...)

1.2 Inclusion of relations between parameters in order to fulfill a geometrical requirement

The number of parameters involved in a complex geometrical requirement may be so high that a subset of acceptable deformation is often of great value. We have to define line of camber versus original reference line, surface of camber versus original plane of reference, volume of dilatation versus original volume. For the zero value of deformation parameter the shape is unchanged, for the 1 value the deformation is such that camber is completely applied. Many such deformations has been currently used in the past ; for example in a wing section change of the thickness or of camber, for a fuselage change in the mean line ...

On the figure 1 is given the family of deformation of a front fuselage when the line of sight of the pilot is changed ; it requires the position of the eye of the pilot, evaluation of the tangent to front fuselage and a camber line that allows such variations and may in addition keep for example the axisymetry of the nose radom and obviously the continuity in curvature at a given reference section of the fuselage.

This deflection of front fuselage for being tangent to a line of variable inclination is a very simple example. Much more complex constraints appear when complete internal architecture appear as a driver for geometrics. For example on figure 2 is given a typical interaction between localisation of radar, canopy, engine with its air intakes ; each

volume has to be specified with appropriate margins : clearance around engine, thickness of the skin of air intake ; one more step in definition has to take in account the structural requirements. For example in figure 2 the description of main frames, spares and ribs allows to express requirements in rigidity or minimal thickness of the structure. An appropriate specification of structural constraints is obtained by inclusion in the geometrical margins of the minimum thickness of structural parts.
The optimization may then cover parameters variations excluding two small carrying loads parts. Again the better description is to define minimal body plus maximal body and to allow variation of parameters constrained by the two extreme body geometry. One typical multidisciplinary optimization may search for maximization of mass of structural parts and minimization of wave and friction drag.

However, such a fixed geometry optimization is not at all convenient for optimality except if a set of points of optimization are selected (not the same for stress analysis and drag analysis). Real design has to take in account the variable geometry imbedded in true active control of aircraft. Such active control may involve three types of actuators : conventional slats and flaps, unconventional active control and jet deflections. In that case different targets may be fulfilled with different sizing requirements : all the devices may include geometry deformation for optimization of aerodynamic characteristics but may induce moments around center of mass. Similarly the conventional control surfaces are generating moments so that they generate angular accelerations taking in account the ellipsoïd of inertia and counteract the moments induced by external perturbations and optimal setting of slat, flap ... with margins for pilot actions. Figure 3 summarizes such constraints on surface, blowing, deflections that are essential parts in optimization of aircraft design. Such interaction of control requirements and basic aerodynamic requirements may be also express as constraints on size of flaps and necessary balance in moment not generally included in basic monodisciplinary design : different of margins for positive thickness of load carrying parts, it may appear as an allocated range of variation between two extreme values of moments covering the range of needed angular acceleration around the three axes.

Major problems of design are related to the boundaries of same topology of geometry : for example the maximum allowable pitching acceleration with an aircraft without tail is bounded by the relative size of main wingbox and elevon size when the aircraft without horizontal tail (i.e. separated flap with increased lever arm) ; but with horizontal tail, it may have more angular acceleration at the expanse of longer rear fuselage.

It is so possible to define a set of topology of aircraft that include each their own boundaries. The better geometrical description have to include a tree of branches, each with fixed topology with steps at bifurcation. The optimization may or may not be converge in the same branch ; if iterations of design converge at points with margins inside the iso-topology boundaries, the topology selected is acceptable ; if not the geometrical constraints along the boundaries will be the main driver in design, with risk of jump to another topology (for example with and without tail).

1.4 Flexibility in design by geometrical finite element method

From such considerations, it appears that the boundaries of constrained iso-topology geometry are first to be considered in design. Flexibility are given by sufficient margins added to that boundaries. Again the boundaries, with or without margins, appear as a reference for later optimization. In the same target of reduction of the number of free parameters in the design, all fixed point, curve, surface has to appear as constrained or fixed parameters : it is a "feature" modeling approach. We have to retain such approach for any multidisciplinary optimization.

A standard "feature modeler" for geometrical definition of aerodynamic shapes is operational from many years in the Dassault design office ; it relies on point, tangent and curvature vectors that define unambiguously the surface of the patches ; surfaces are fitted in curvature along the three dimensional parametric splines at the boundaries of each finite element patch.With such a vector definition any transformation of the space may give a new vector set by applying linear operator (matrix) coming from local distorsion of space : it allows a "feature" modeling to be easily generated. The transformation of the space may itself defined as a two "point" homothetic or affin projection along a camber line or surface, covering the boundary of topology as previously defined. Figure 4 summaries such modeler characteristics.

2. A RATIONAL APPROACH BY MATHEMATICS

2.1 General problem of optimum design

If it is possible to define explicitly the index of performance, the constraints, the state equations, it exists a rational procedure to derive the optimal set of geometric parameters giving the optimal shape for the body.

However one single optimum shape exist and that the "optimum optimorum" of the shapes may easily be

obtained if the cost function has a great number of local minima.

- The time of computation is tractable with present computer in as much that there is no exact solution to determination of flow with real Reynolds number accessible to computation for a long time, and that approximate solution with Reynolds average flow is also generally impossible to compute accurately with present computers.

- The constraints may be expressed with sufficient accuracy leading to realistic design.
- The optimal shape is stable for a small variation in cost fonction, constraints, external conditions or set of parameters fixed as representative of physics modelised.

Generally the designers avoid such cumulated uncertainties on the existence of an optimum design by taking as an initial point a design well known as robust and not so far from optimum, and trying to select a better design by iterative procedure. Of great help is however the research of local optimum with simplified analysis, giving more precise answer on a partial shape design. For example the selection of an optimum aerodynamic wing section may help greatly to design a wing for conditions too costly to be completely computed in 3D. The result of complex wing section design may then be transformed in a simplified cost function on pressure distribution, pressure gradient with penalty on lift and pitching moment.

If we turn to elasticity equation for materials and Maxwell equation for electromagnetics it is possible in the same way to simplify the geometry of load carrying parts, of antennas or bodies, to reduce the number of modes and of the frequencies, to assume ray tracing or simplified collapse criteria and so to have access on suboptimal parameter optimization. For example optimization of flutter speed or of radar cross section for fuselage section may be obtained at a realistic cost/time of supercomputer.

From a mathematical point of view, it can be seen as an optimization with a simplified set of state equations and with an alternate direction descent.
Such approach will be generally the only realistic optimization procedure for many years due to the complexity of state equations.
However computation of "not far from optimum" shape is possible if the number of parameters is not too large with a mix of such simplified optimum design and direct descent for small number of parameters.
If the cost function is sufficiently simple, its derivative may be evaluated and the cost of computation of the adjoint state of Euler, elasticity, Maxwell equation is not too large ; then an optimal shape may be obtained iteratively for a cost equivalent at each step to some direct computations.
If the cost function is complex, and impossible to be derived, amongst a family of optimal shape with reduced number of parameters (typically less than 20) it is possible to select iteratively a better set of parameters defining a better shape.

2.2 Steepest descent to optimum multi-disciplinary shape

If we take the process of alternate descent, one with optimum design with derivable simplified cost function, the other with reduced number of parameters descent, the major time of computation will come from the later ; the sensitivities may then be compared, giving evaluation of uncertainties on critical parameters

There is three ways for solving such descent problem :

- The first one is to rebuild derivative from discrete variations. in that case, an estimate of the local constant cost curve will be obtained and a discrete conjugate gradient procedure may be initiated.

- The second one is to assume that the cost function is near optimum and so quadratic (or second order) versus the parameters. One fit a second order approximation of the cost function to the available cost values already computed for a set of parameters ; this optimum bowl will be more precise at each new computation and will give more effective determination of optimum set of parameters than conjugate gradient because all the points will contribute to the knowledge of the cost function.

- The third one is to mix heuristic and learning process in search of optimum. One way is the use of genetic algorithm : the new set of parameters will have an heavier weight as far as it will be better in cost evaluation. However that heuristic process is poor when deterministic cost function is to be addressed : the final convergence is slow (in square root of n) whereas it is steepest when a continuous convexity is present as usually. An approximation of cost function by neural network may also be used but it is not so effective as for dynamic system optimization.

2.3 Constrained optimization

If one make detailed analysis of the convergence towards optimum design, two cases appear :

- Optimum shape is between the constrained margins of variations of the parameters allowed by the different constraints in geometry or equivalent simplified cost boundaries. In that case, the process will be as much efficient as the parameters will be in small number, taken in a family of suboptimal shapes (for example smooth curvature family, including optimum shape previously obtained).

- Optimum shape is in constrained conditions. It is generally the case when the design is good, because the maximum of efficiency is to be compromised with other constraint. In that case, it will be better to follow the surface of constrained parameters because it has a lower number of degree of freedom.

For example, the optimal wing section will be in a family function mainly of maximum thickness, and such family will be bounded by the design Mach number and the weight of the wing box and its fuel capacity.
But the root of the wing will be deduced from that external wing section differently following the constraints in wing-fuselage shape intersection and respective degree of freedom (Figure 5).

2.4 Flexibility and robustness in design - least regret optimization

One important output of optimum design is the sensitivity to parameters. It will give the stiffness of the performance / geometry relation. Decrease of such stiffness relation will give more robustness to the design.

In the same direction, the adjoint equation will give information to the best location of sensor and actuator on the aircraft. The better actuation for an active aerodynamic control will be obtained by increase of the function of the adjoint equation at the location of the actuator, and it can be also a design driver to optimally select the actuators.

Anyway the optimal design will be more robust by multipoint design and by variable setting of slat and flap (variable geometry) around optimal shape as may be intuitively seen in Figure 6.

One way of expressing the robustness versus multidisciplinary optimization is the "least regret optimization". It corresponds to the concept of :

- maximisation of performance index in aerodynamics
- minimisation of sensitivity to other constraints or maximisation of the distance to the constraints.

Not far from optimum design for performance index is a "without-important-losses" improvement of the margins near critical constraints.

3. CONSTRAINTS OF PHYSICS

In the same manner that we have addressed specially the changes in topology in the geometrical expression of constraints, we need to delineate the boundaries of homogeneous physical subdomains (Figure 7).

Such subdomains are defined in the following manner :

- A boundary in a physical set of parameters is to be identified each time that a topology change occurs in the flow (in aerodynamics), in the deformations (type or mode of buckling or collapse in material analysis) or in wave propagation (diffraction vs reflection in electromagnetics)

- The boundaries are to be defined at the size larger than the phenomena observed in the modelling approach or at a smaller size if amplification takes place and appears in larger size.

- The boundaries are to be defined with the set of physical parameters relevant to the physics (Mach and Reynolds number, characteristic lengths or frequencies ...).

With the help of such domains, it is now possible to make a checking of the trajectory of the optimization process :

If it is bounded only by geometrical constraints validity of simulation may be established by validation of the codes on a : - same topology in geometry, same topology in physics - experiment.

If it is bounded by physics constraints, it is necessary to make evaluation of the jump of properties that comes from the change in topology. If there is a continuous behaviour of physical properties, it is just a matter of evaluation of the eventual effect of induced non-linearity on flight vehicle.

If there is a discontinuous behaviour of physical properties, perhaps it will be better to limit the acceptable physics by a constraint on physical parameter for avoiding optimization with such irregular output. For example a irregular instant jump in shock location or in separation line is against robustness in the optimization point.

Such a survey of the physics will be more and more a critical output, that need careful analysis by specialist in order to have assessment of the validity of optimal shapes output by computer.

4. TOOLS FOR MULTIDISCIPLINARY MULTI-COMPANY OPTIMIZATION

4.1. Multi-company design

The merging of different complementary companies not avoid in Europe the necessity to push high technology everywhere and the fact that aerospace insdustry is a traditional leader for such high technology emergence at the industrial level. So it is fruitfull for all european countries to be participants in some part of the high technology improvements induced by aerospace product engineering.

The answer by a centralised design office somewhere is not a good answer as far as the research on the physics is now correctly spread in all countries of EEC, and the research in systems is part of a general effort for mastering complex systems that will be present in all the advanced product of the future. For the architect (Table I) it is clear that the numerical model and the virtual product approach will help to exchange the mechanical interfaces for a large spreading of the work in the development phasis of any new project.

One major concept is emerging in management of complexity of advanced systems : the identification of the number and complexity of the interfaces will be the major critical output of preliminary design. Such complexity has to be mastered at the begining. It comes from the interaction of the components in greater number N than in the past and of interaction of larger number of specialists. It is to be reminded that N components gives birth to N ! interfaces that is a very large number as soon as N is not small number. Complexity comes from such combinatorial explosion and not of interaction of parts that constitue a chain :. a chain of N wagons has only N interfaces that can be normalized with just one interface standard, and it is the same for clock gears except that unique standard is not possible, each gear having a specific size and function. Complexity is not present, just complication, with N interface. Moreover the gear work as a discrete linear additioner ; such linear behaviour is not generally true for the parts of a complex system as an aircraft.

By consideration of linearized equations, it is possible to define a linear matrix interface that will be able to reduce the interaction to a linear operator and so to work with easy exchange of complete interface characteristics. For non-linear behaviour the complexity is "emerging" and only direct simulation of the complete system (with appropriate modelling of smaller sizes) may answer to the need of a global prediction of the system performances.

4.2 Common centers of computations and simulation

The only way of doing that global work will be to exchange modele of complete aircraft ; however if dynamic analysis is needed (separation of stores, transient loads, aerodistorsion and effect on lobes of antennas ...) the data and code exchanged is great and may engage the know-how of a company. So the best way is to keep the codes unaccessible to other partners but to open the total results exactly as it will happens in flight test many years after. Such integration of the best of modeling in a virtual physics simulator is mandatory for in advance evaluation of performances and above all for substantiation of the critical points of the design.
If, for example, margins are to be kept, with a least regrets approach in the optimisation, such a global fine grain simulation is needed. Convenient protection may be achieved by a common center of simulation where a super computer will receive proprietary codes from different partners and share only the global result of their work together : an agreed supervisor, plus access available only with multiple keys and separate proprietary code and data disk storage is a convenient solution to that problem.

The iteration optimization, with an agreed cost function is a good way of design in such multidisciplinary and multicompany situation. It affords to an international design team the same capability of managing as soon as possible the critical issues of the program as in a single company ; moreover various specialist teams may be involved in a sparse matrix of interaction for each company and in a complete set only for the managing team of the project. It requires an affordable C.S.C.W (Computing Support to Cooperative Work)

Due to the difficulty in validation of such complex numerical simulation tools, it seems useful to have alternate codes for critical computations ; so each partner is increasing the confidence in global answer, the global output alone being accessible to all partners.

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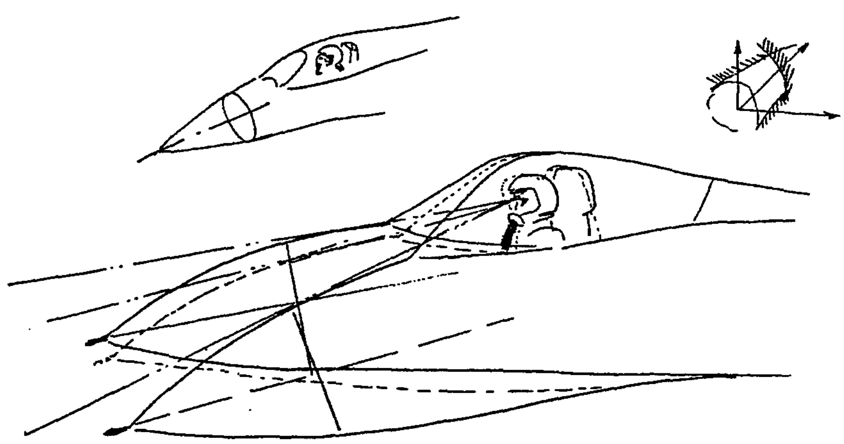
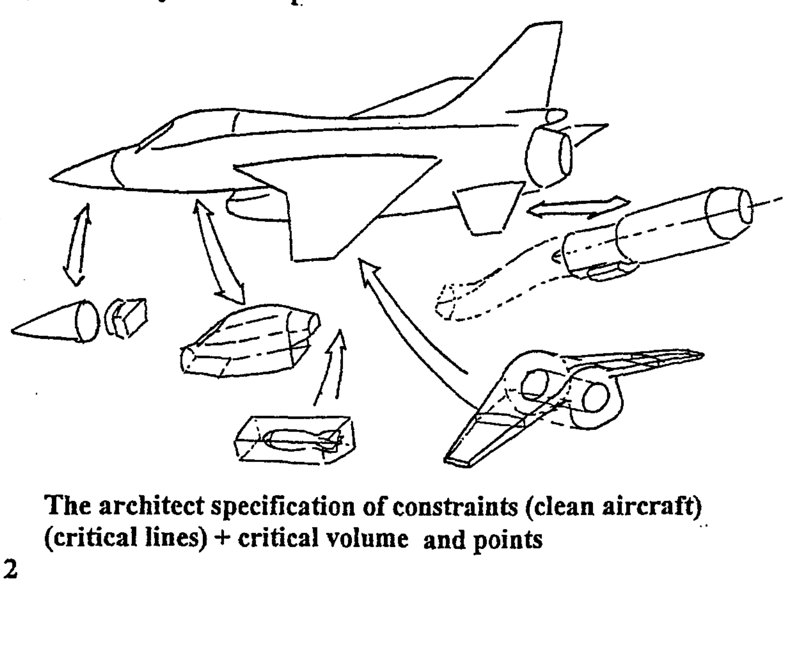


Change in a front fuselage with constraint on the line of sight
Figure 1

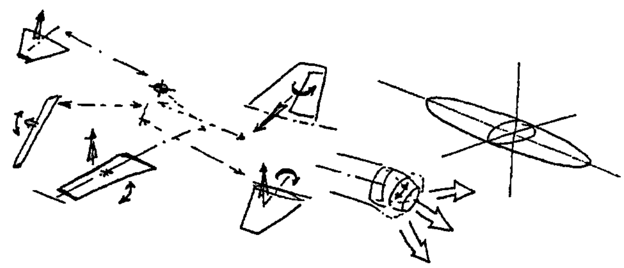
Variable aerodynamic shape



The architect specification of constraints (clean aircraft)
(critical lines) + critical volume and points

Figure 2

The architect specification of constraints (control of aircraft)
hinge lines + moments



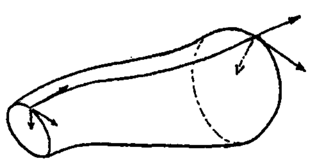
Variable setting of control surfaces

Variable setting of nozzle

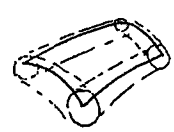
Figure 3

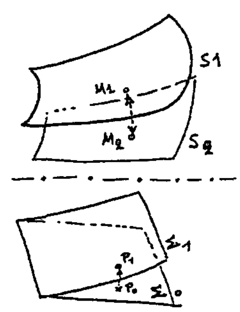
Inertia ellipsoïd

Standard Dassault Modeler (David),



Ellipsoïd - bounded local
surface attached to a spline

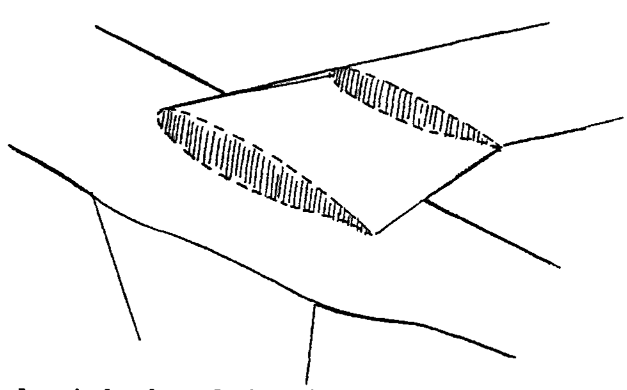




Finite Element Surface

Transformation S1 → S2
as generated by a Σ0-Σ1 distorsion

Figure 4



Constrained optimization of wing fuselage

Figure 5

Multipoint and least regret optimization

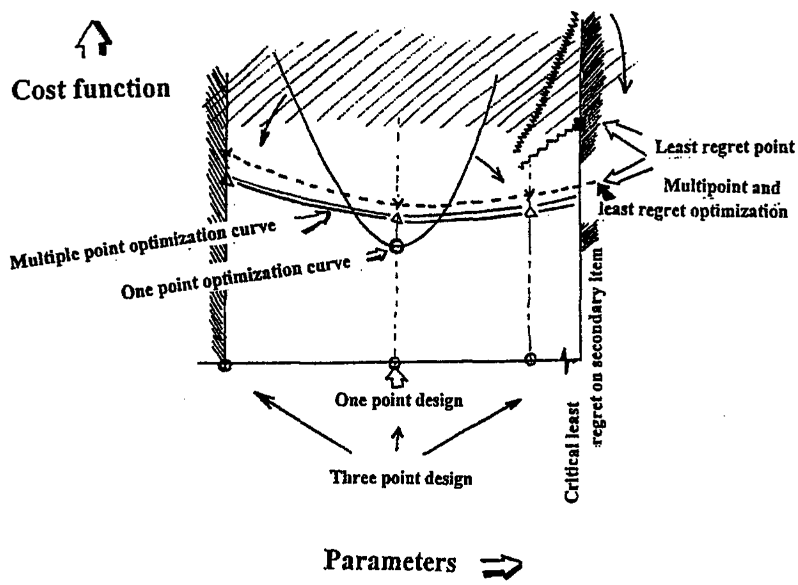


Figure 6

Constraints in physics parameters

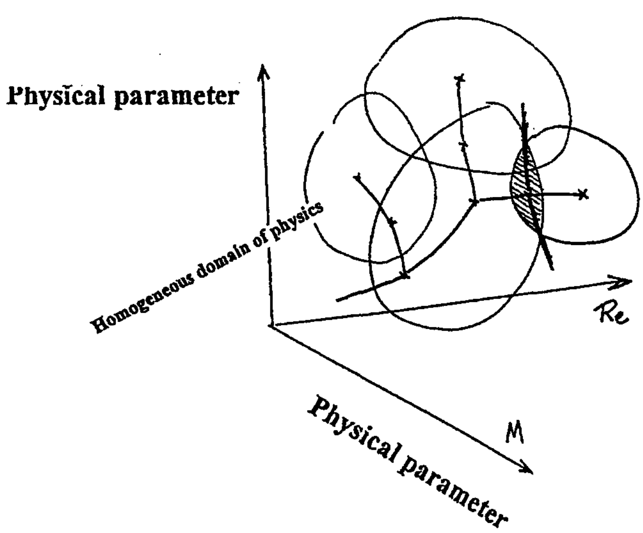


Figure 7

DISCUSSION

Session II, Paper #10

Prof Slooff (NLR, Netherlands) sought the author's opinion on the usefulness of "fuzzy logic" in the optimization process.

> **Mr Perrier** believed that fuzzy logic was a way to transform an unknown function joining definite extremal states into a derivable function. He was concerned over determinisation in an optimization process could be dangerous unless the smoothing function helps the convergence. However, how is this function reliably to be selected?